Super Flavour Factory Round Table – The SuperB Physics Programme

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SuperB is a proposed high luminosity Super Flavour Factory capable of accumulating $75\,\mathrm{ab}^{-1}$ of data at the $\Upsilon(4S)$ as well as at other center of mass energies. These proceedings summarise highlights of the SuperB physics programme, and in particular there is emphasis on the unique aspects of SuperB over other planned or existing experiments.

1. INTRODUCTION

SuperB is a proposed high luminosity e^+e^- collider with a design luminosity of $10^{36}cm^{-2}s^{-1}$. This experiment will accumulate $75\,\mathrm{ab}^{-1}$ of data at the $\Upsilon(4S)$ with five nominal years of data taking, which is approximately 65 times the combined BABAR and Belle data sample at this energy. In addition to accumulating data at the $\Upsilon(4S)$, SuperB will run at energies from charm threshold, $\psi(3770)$, to the $\Upsilon(6S)$. The e^+e^- collider will have an 80% polarised electron beam, that also has significant impact on the physics potential of this experiment. The broad physics programme of SuperB is described in Ref. [1]. The SuperB accelerator complex is described in [2,3], and the detector concept is reviewed in [4].

While the baseline luminosity is $10^{36}cm^{-2}s^{-1}$, if the accelerator is able to achieve this performance with the nominal lattice parameters, there is a significant potential to upgrade the luminosity by a factor of four over the lifetime of the experiment.

SuperB is a natural successor to the BABAR, Belle, and BES-III experiments, as it will accumulate about two orders of magnitude data more than these experiments will have delivered during their lifetimes. There is competitor experiment to SuperB, called Belle II, which is in the early stages of being constructed and aims to accumulate about $50\,\mathrm{ab}^{-1}$ during its lifetime. The physics potential of Belle II can be found in Refs. [5,6]. The main advantages of SuperB over other experiments are discussed in Section 2.

The remainder of these proceedings discuss highlights of the B physics programme (Section 3), the potential of Charm Physics in general and at the $\psi(3770)$ (Section 4), precision electroweak measurements, in particular the potential to measure $\sin^2\theta_W$ (Section 5), benefits of beam polarisation to the τ physics programme (Section 6), and the potential for direct searches and SM spectroscopy studies (Section 7). A difficult aspect of the physics programme of SuperB is the phenomenological archaeology that will be required to try and elucidate new physics should it be manifest in the data. Our current understanding of how this may work is summarised in Section 8. It should be noted that these sections concentrate mostly on the unique features of the SuperB experiment as examples of the wider programme. The final section of these proceedings provides a brief summary of the highlights of this work.

2. Overview of the Physics Programme

The physics programme of SuperB can be summarised as the search for direct and indirect signs of physics beyond the Standard Model (SM), generically referred to as *new physics*, while simultaneously performing precision tests of the SM [1]. The searches for new physics are sensitive to particles with masses far in excess of the reach of LHC experiments, Lepton Flavour Violating (LFV) processes in the τ sector, on mass shell light dark matter and light Higgs candidates, and manifestations of so-called Dark Forces. More detail on the complete programme can be found

in Refs. [1] and [7] which contain details of the physics programme common to both Belle II and Super$B$. A theoretical overview of the physics case for Super Flavour Factories can be found in Ref. [8].

The following aspects of this programme are unique:

- A larger baseline data set than any proposed experiment at these energies. With the additional data that Super$B$ aims to integrate within five years of nominal running, one should be able to observe several rare decays that are sensitive to new physics, if those decays occur at the expected SM rate. These rare decays may play an important role in constraining details of the new physics Lagrangian.

- The ability to run at the $\psi(3770)$ which corresponds to charm threshold. This opens up the possibility to study time-dependent CP asymmetries in $D^0\overline{D}^0$ decays in analogy to the CP violation studies that have been done at the existing B factories. In addition to this unique potential, by accumulating a large sample of data at the $\psi(3770)$, one will be able to make precision measurements of a number of decay constants and other parameters. These will improve theoretical understanding of experimental programmes at LHCb and the Super Flavour Factories, in particular the measurements of γ, and of charm mixing. Many of these measurements will be useful in validating Lattice QCD and theoretical frameworks, and in parallel many rare decay studies will be able to provide constraints on new physics.

- By having a polarised electron beam, it is possible to make precision tests of the electroweak sector that complement SLC and LEP measurements of $\sin^2\theta_W$. The benefit of having such a measurement is that it is essentially free from theoretical uncertainties. The polarised electron beam will enable one to reconstruct the τ polarisation, and use this information as a discriminating variable when searching for lepton flavour

violating processes. One will also be able to measure the τ EDM and $g-2$ using these data.

Once the design goals of Super$B$ have been achieved, there is scope to increase luminosity by up to a factor of four. If that is realisable then, just as with the B factories, the physics programme of Super$B$ will expand significantly. Those measurements of rare processes or small effects that would have been marginal in terms of sensitivity with $75\,\mathrm{ab}^{-1}$ would provide very significant constraints to further our understanding of nature at high energy if one accumulates several hundred ab^{-1}. The precision of measurements that are central to the physics programme of this experiment would also be surpassed in almost all circumstances. As with any frontier, by pushing the intensity to a new level, one would be exposed to additional opportunities to constrain nature.

Super$B$ will be able to cover a wider range of measurements than the Belle II experiment, with more data. Where there is overlap between the programmes of these two experiments, one can expect a repeat of the excellent synergies that existed between the LEP experiments, BABAR and Belle, and will no doubt be present at the LHC in coming years. The dedicated flavour experiment at the LHC, called LHCb, will mostly probe complementary flavour observables to Super$B$. In the few cases where there is overlap between these experimental programmes, again that will provide a useful cross check of performance, and as noted above, measurements from Super$B$ will play an important role in controlling theoretical uncertainties associated with the interpretation of some of the results from LHCb.

Measurements from Super$B$ will have ramifications for both fundamental particle physics and cosmology. Many of these results will help us understand the flavour sector of the SM and new physics scenarios, which in turn may have relevance for the matter-antimatter asymmetry problem, and the origin of the Universe. Studies of rare decays may help elucidate the type of new physics and energy scale that this occurs at. Precision measurements of $\sin^2\theta_W$, are related to the electroweak symmetry breaking (EWSB) process,

central to the SM, and searches for light Higgs particles may elucidate EWSB beyond the SM. In addition to these, one can elucidate Dark Matter and Dark Forces postulates, as well as probing the effects of quantum gravity through precision tests of CPT in B, D, and τ decays. Tests of other fundamental symmetries, such as lepton universality may also yield a surprise.

Table 1 gives a summary of expectations for some of the main measurements to be made at Super$B$. The following sections discuss some of the unique features of the physics programme of this experiment in more detail.

Table 1
A summary of expected precision obtained for a number of benchmark channels at Super$B$. See Ref. [1] for a more comprehensive overview. B_s measurements assume 1 (30) ab^{-1} of data at the $\Upsilon(5S)$, and the charm prospects assume that in addition to $\Upsilon(4S)$ data, one has accumulated a sample of 500 fb^{-1} of data at $\psi(3770)$.

Measurement	Precision
B Decays	
$B \to K\nu\overline{\nu}$	observe
$B \to K^*\nu\overline{\nu}$	observe
$\Delta S(\eta' K^0)$	± 0.02
$\beta(c\overline{c}s)$	$0.1°$
α	$1 - 2°$
γ	$1 - 2°$
A_{SL}^s	0.006 (0.004)
$B_s \to \gamma\gamma$	38% (7%)
Charm	
x_D	$\pm 2.0 \times 10^{-4}$
y_D	$\pm 1.2 \times 10^{-4}$
Precision Electroweak	
$\sin^2 \theta_W$ $(\sqrt{s} = m_{\Upsilon(4S)})$	1%
τ Physics	
$\tau \to \mu\gamma$	$\mathcal{B} < 2.4 \times 10^{-9}$
$\tau \to e\gamma$	$\mathcal{B} < 2.4 \times 10^{-9}$
$\tau \to \ell\ell\ell$	$\mathcal{B} < 2 - 8 \times 10^{-10}$

3. B Physics

A number of rare B decays are sensitive to new physics through loops or Flavour Changing Neutral Current (FCNC) processes. In particular decays with suppressed SM amplitudes, that could interfere with significant non-SM amplitudes could be sensitive probes of new physics. There are a number of such channels, with interesting observables ranging from branching fractions and forward-backward asymmetries, to time-dependent CP asymmetry parameters discussed in Ref. [1]. One particular example that is a golden channel for Super$B$ is $B \to K^{(*)}\nu\overline{\nu}$. In order to observe these decays occurring at a SM rate, one needs to accumulate of the order of 75 ab^{-1} of data. With such an observation it would be possible to measure the branching fractions of both $B \to K\nu\overline{\nu}$ and $B \to K^*\nu\overline{\nu}$, as well as the fraction of longitudinally polarised events f_L in the latter mode. An experiment with a smaller data sample would not be able to measure all of these observables. The corresponding constraint obtained on the new physics parameters ϵ and η (see Ref. [9]) are shown in Figure 1.
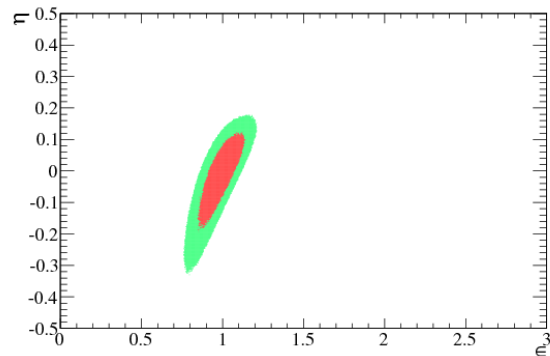

Figure 1. Expected constraints the new physics parameters ϵ and η using $B \to K^{(*)}\nu\overline{\nu}$ decays at Super$B$ (not including the measurement of f_L from the K^* mode). The SM solution corresponds to the point $(\epsilon, \eta) = (1, 0)$.

While many of the measurements at Super$B$ will focus on detailed studies of CP violation, one should not neglect the possibility that CPT is violated. This symmetry, while conserved in the SM as a result of the intrinsic Lorentz structure of the model, can be violated in scenarios beyond the SM, for example [10]. Super$B$ will be able to produce more stringent constraints on CPT in $B^0\overline{B}^0$ oscillations than previous experiments, reaching a precision of $0.3 - 0.6$ per mille on the real and imaginary parts of the CPT violating mixing parameter z.

In addition to the aforementioned searches for new physics, one should also recall that it will be possible to perform precision tests of the CKM mechanism using both direct and indirect constraints on the unitarity triangle. The observables accessible to a Super Flavour Factory include several different measurements of all of the angles (α, β, γ)[1], as well as measurements of V_{ub}, V_{cb}, V_{ts}, and V_{td}. No other type of flavour experiment is able to perform such a set of measurements. For this reason, both Super$B$ and Belle II will provide powerful set of precision constraints on the description of CP violation and quark mixing in the SM. Ref. [1] contains more details on this part of the Super$B$ physics programme.

4. Charm Physics

The discovery of mixing in neutral D mesons has a profound implication on the phenomenology of charm decays. As with neutral kaons and B mesons, the establishment of mixing, which is interesting in its own right, also brings the potential for many new CP violating observables to be studied at future experiments. Precision measurements of D mixing will be possible at Super$B$, in addition to searching for CP violation in D mesons. Such measurements would be the only probes of CP asymmetries involving transitions of an up-type quark. CP violation in charm decays within the SM is expected to be a small effect, as the CKM matrix elements involved in c quark transitions are mostly real, where imaginary components related to the CKM phase only become

apparent at order λ^4 [11]. If the CKM scenario is able to accurately predict CP violation phenomena in the charm sector, then this will strengthen the case that this is indeed the dominant description of quark mixing in the SM. Any deviation from SM expectations would yield a clear signature for NP.

Using only data from the $\Upsilon(4S)$, one would expect to be able to measure mixing parameters in the charm sector x_D and y_D to a precision of 4.2×10^{-4}, and 1.7×10^{-4}, assuming realistic input of information on strong phase differences from BES III or using data collected by Super$B$ at the $\psi(3770)$. More details of this estimate can be found in Ref. [1].

4.1. Charm Physics at the $\psi(3770)$

A sample of $500\,\text{fb}^{-1}$ of data (50 times the data sample expected at the BES-III experiment) could be accumulated at the $\psi(3370)$ over a period of a few months using Super$B$. The applications of this data are far-reaching, and go beyond the current CLEOc and BES-III programmes at the $\psi(3770)$. One advantage of studying charm decays at low energy is the relative lack of background, when compared to data accumulated at a higher energy resonance such as the $\Upsilon(4S)$. This is clearly manifest through the competitiveness of CLEOc in a number of measurements of charm decays, when compared to the results from BABAR and Belle on a number of branching fraction and decay constant measurements. The combination of kinematic constraint, tagged D mesons, and a clean experimental environment make the $\psi(3770)$ a versatile laboratory to test many aspects of the SM and search for new physics.

Ever since the B factories established mixing in the $D^0\overline{D}^0$ system, the possibility of utilising quantum correlations at charm threshold (the $\psi(3770)$ resonance) for time-dependent measurements has been a possibility. The physics sensitivity to CP asymmetries at charm threshold is under investigation.

Measurements of strong phases in Dalitz decays at Super$B$ will play a significant role in reducing theoretical uncertainties in the measurements of γ and charm mixing at Super Flavour Factories and LHCb. Similarly measurements of decay

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[1] The alternate notation of (ϕ_1, ϕ_2, ϕ_3) = (β, α, γ) may also found in the literature.

constants and rare decays from data collected at charm threshold will help tune theoretical tools that will be used elsewhere.

Other fundamental measurements that will be made include testing the CPT symmetry, which could be violated through de-coherence of quantum correlations [12], or as the result of Lorentz violation in high energy theories [10].

In analogy with rare B decays, one will be able to constrain new physics scenarios using rare D decays. Here the advantage that Super$B$ has over other experiments such as Belle II and LHCb is the ability to cleanly extract signals, and the data sample accumulated at Super$B$ will be fifty times larger than that expected at BES III. This large data sample is particularly important when searching for rare or forbidden decays. Finally, it is possible to make significant improvements on the precision of charm mixing parameters by using both data from the $\Upsilon(4S)$ and from the $\psi(3770)$.

Using data from the $\psi(3770)$ and the $\Upsilon(4S)$, one would expect to be able to measure mixing parameters in the charm sector x_D and y_D to a precision of 2.0×10^{-4}, and 1.2×10^{-4}. The potential of Super$B$ for charm mixing parameters is illustrated in Figure 2. More details of this estimate can be found in Ref. [1].

5. Precision Electroweak Physics

The Weinberg angle resulting from electroweak symmetry breaking has been measured precisely at SLC and LEP [13,14], through the study of $e^+e^- \to f\bar{f}$ at the Z^0 pole, where f is a fermion. Interpretation of this result as a measure of $\sin^2\theta_W$ relies on understanding small hadronic uncertainties at the Z^0. It is possible to perform a precision measurement of $\sin^2\theta_W$ using the left right asymmetry method employed by SLC for $e^+e^- \to \mu^+\mu^-$, $\tau^+\tau^-$, and $c\bar{c}$ transitions at the $\Upsilon(4S)$, where theoretical uncertainties are negligible. In order to do this, one must have a polarised electron beam, as is the case for Super$B$. Assuming that the electron polarisation is 80% and that the uncertainty on the measured polarisation is below 1%, then Super$B$ should be able to perform a measurement of $\sin^2\theta_W$ with un-

certainty of the order of 0.0002 using di-muons. Measurements with τ and charm quark pairs can also be made, but with less precision. For comparison, the SLC result in Ref. [13] is $\sin^2\theta_W = 0.23098 \pm 0.00026$. Thus Super$B$ will be able to measure this fundamental parameter at a center of mass energy of 10.58 GeV with precision comparable to the existing measurements at the Z^0. In addition to measuring this parameter, it will be possible to test neutral current universality to high precision, and probe new physics scenarios, for example models with Z'. More details can be found in Ref. [1] and references therein.

6. τ physics programme

Super$B$ has a broad τ physics programme ranging from searches for Lepton Flavour Violation (LFV), and CP violation, through to a number of precision tests of the Standard Model, including lepton universality tests and CPT.

Given polarised electrons, it is possible to determine the polarisation of τ leptons in Super$B$. As a result, the reconstructed helicity angle distribution for τ decays can be used as a discriminating variable to suppress background. This feature of τ analyses at Super$B$ will enable searches for the Lepton Flavour Violating decays of $\tau \to \ell\gamma$, where $\ell = e, \mu$ to be performed down to a level of a few 10^{-9}. With regard to $\tau \to 3\ell$, the anticipated upper limits are $2 - 8 \times 10^{-10}$, depending on the three lepton final state.

With regard to other τ measurements, the polarisation enables one to measure the τ EDM and $g - 2$ parameters, with anticipated sensitivity of $17 - 34 \times 10^{-20}$ for the EDM, and a precision of a few $\times 10^{-6}$ for $g - 2$. More details of the τ physics programme at Super$B$ can be found in Ref. [1].

7. Direct Searches and Spectroscopy

While the majority of new physics searches at Super$B$ concentrate on the potential for an indirect discovery, there is a class of light new particles that may be directly manifest in the data. These are light scalar particles that either fall into the category of a light dark matter candidate, or a light Higgs particle [15,16,17,18,19,20]. Dark
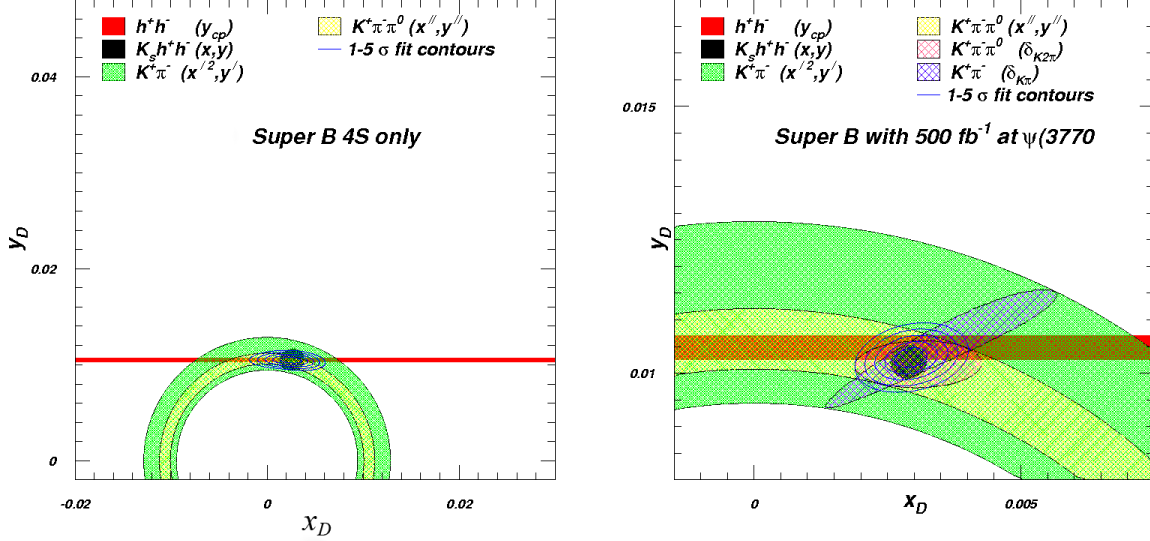
Figure 2. Constraints on charm mixing expected at Super$B$ using (left) only data accumulated at the $\Upsilon(4S)$, and (right) also using data from the $\psi(3770)$.

matter could be light, and have gone undetected by experiments so far, if it couples weakly to the Z^0. Many extensions of the SM introduce several Higgs particles, and in extensions to MSSM it is possible for some of these to be lighter than twice the b mass. Thus searches for both light Dark Matter (with masses less than about 5 GeV) and light Higgs particles at Super$B$ are essential in order to constrain their possible existence.

In addition to direct searches for manifestations of dark matter, it is possible to indirectly search for possible evidence of so-called dark force, with an associated hidden sector [22,23]. This concept has recently emerged, and is rapidly evolving field that is being tested by data from both astro-particle and particle physics experiments. In this model dark matter particles with masses less than the TeV scale can annihilate in order to create a dark photon A', a gauge boson with mass of ~ 1 GeV. The dark photon can then decay into SM particles, and if the mass of the A' is below twice the mass of the proton, then A' is expected to decay into di-e, μ, or π final states. As with light

Higgs, and light dark matter, Super$B$ will be instrumental in constraining models of dark forces.

In terms of SM spectroscopy, as was the case with the existing B factories, Super$B$ will be able to perform a wide range of searches for, and precision measurements of light mesons and exotic particles. These studies commenced with Belle's discovery of the X(3872) [24], and a second boost to this activity was initiated by the discovery of the Y(4260) in the study of $J/\psi\pi\pi$ using ISR data at BABAR [25]. As a result of the current plethora of activity there are a number of outstanding issues. While the masses and widths of many of these particles are now well know, in some cases there remain issues with the determination of spin-parity assignments, and understanding the primary branching fractions of these. Other outstanding issues range from simply confirming the existence of a particle, as is the case of the recently observed $Z^+(4430)$ [26] to determining their underlying nature. By understanding the underlying nature of some of these particles, one could make significant steps forward in our

understanding of QCD, and in testing the framework of Lattice QCD.

8. Elucidating new physics

There are a vast number of observables that will be measured at SuperB in B, D, τ, Υ(nS) decays, as well as using other light mesons and baryons. Measurements of rare decays, that are loop, or Flavour Changing Neutral Current (FCNC) dominated can be used to constrain many different types of new physics. In analogy to the way that FCNCs have shaped our understanding of the SM, these will shape understanding of new physics models. Precision tests of CP conjugate processes probe phase information of the CKM mechanism in the quark sector. In the charged lepton sector one is able to constrain possible LFV through searches for forbidden transitions in τ decays. The common coupling of charged leptons, irrespective of species, in the SM has been tested with some precision already in a number of possible ways. Studies of light mesons, including Υ(nS) decays to di-lepton final states can be used to increase the precision of these constraints and further test the validity of this symmetry. Our physical framework is built upon the concept of Lorentz invariance, and recently there have been attempts to go beyond this constraint in order to understand high energy theories such as quantum gravity. A consequence of Lorentz invariance is the conservation of the CPT symmetry. This symmetry can be tested in B, D, and τ decays at SuperB, to complement the tests planned and already performed at the previous generation of B factories, and in the kaon system through experiments such as CP-LEAR, KLOE, and KLOE-2. If a CPT violation signal were to be found, this could have profound impact on our understanding of the foundations of physics. Similarly any positive result of a direct search for dark matter candidates would have a profound impact on the understanding of both particle and astro-particle physics.

Ultimately if no deviations from the SM are found in data collected at SuperB, then we shall be no closer to understanding the nature of new physics at high energy. However this outcome is not is not a bleak one, as a number of erroneous theories may have been ruled out by measurement, and any remaining candidate theory of new physics would be strongly constrained by those very measurements found to be compatible with the SM. In turn SuperB would have performed a precision test of the electroweak and flavour sectors of the SM.

Considering the SM confirmation scenario, it is worth noting that this is the most versatile experiment proposed to perform precision tests of the CKM mechanism. One is able to extract measurements of several of the matrix elements through both inclusive and exclusive analyses, measure all of the angles of the unitarity triangle to the level of, or better than, a degree, complement these measurements with information from a number of rare decays, of both B and D mesons, and provide information that will help the interpretation of some of these measurements.

Section 10 of Ref. [1], and references therein, discuss current theoretical understanding of how one can take sub-sets of the measurements described above to discriminate between sub-sets of possible new physics scenarios. Phenomenological work is on going with regard to this problem, with the ultimate goal of being able to combine measurements in a global way in order to satisfy particle physics and cosmological constraints of this data.

9. Summary

The proposed SuperB experiment is a versatile Super Flavour Factory with the potential to provide many complementary constraints on new physics scenarios to elucidate our understanding of physics beyond the Standard Model. Details of the SuperB physics programme are reported in Ref. [1]. The potential of SuperB goes beyond that of the Belle II experiment, which has recently had funding approved for an initial phase of accumulating data. The ultimate goal of Belle II is to accumulate $50\,\mathrm{ab}^{-1}$ of data at the Υ(4S) as well as investigating other Υ(nS) resonances by 2020. The goal of SuperB is to integrate $75\,\mathrm{ab}^{-1}$ of data at the Υ(4S) on a similar time scale, and to run at the ψ(3770) as well as at other Υ(nS)

resonances. If the nominal luminosity for Super$B$ can be achieved using the baseline design, it may be possible for Super$B$ to reach a luminosity four times the design goal subsequent to this initial phase.

In addition to the larger integrated luminosity target of Super$B$, the electron beam will be 80% polarised. This opens up the possibilities of being able to measure $\sin^2 \theta_W$ precisely at both the $\Upsilon(4S)$ and $\psi(3770)$. Such a measurement at the $\Upsilon(4S)$ would be theoretically clean and with a similar precision to the corresponding LEP result at the Z pole.

In terms of the physics programme at the $\psi(3770)$, pairs of neutral D mesons will be created in a quantum-correlated state in analogy with B^0 production at the $\Upsilon(4S)$. This opens up the possibility of studying time-dependent CP asymmetries at charm threshold. In addition to this, one will be able to precisely measure decay constants and branching fractions of light D mesons. Some of these measurements will impact on theoretical uncertainties that affect measurements within the B physics programmes of the Super Flavour Factories and LHCb.

With regard to spectroscopy measurements, there are a number of outstanding issues as a result of the recent work published by the current B factories. A prime example of this is the confirmation of the $Z^+(4430)$, recently discovered by Belle. With one hundred times the data, these issues should be better understood. In addition to the SM spectroscopy, Super$B$ will also be able to place interesting constraints on light scalar Dark Matter or Higgs scenarios, as well as Dark Forces.

The Super$B$ experiment has the ability to measure more observables related to quark and lepton flavour, electroweak symmetry breaking and dark matter, than any other proposed or existing flavour experiment. Highlights of the physics potential reported in Ref. [1] have been recapitulated here. Using the measurements proposed we will ultimately be able to strongly constrain or discover a sign of physics beyond the SM. In the case where one finds no deviation from the SM, then the resulting set of measurements obtained will place stringent constraints on model builders concerned with constructing a theory of

particle interactions at high energy or in the early universe.

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